MODULATIONS OF FIBER PROPERTIES BY GROWTH ENVIRONMENT THAT PERSIST AS VARIATIONS OF FIBER AND YARN QUALITY.

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Abstract

Under the general agreement that growth environment significantly affects cotton fiber yield, breeders and agronomists have collaborated to maximize fiber yield over a wide range of growth conditions. Growers also accept the concept that fiber properties such as micronaire and maturity are modified by the environment in which the fiber is produced. However, the nature and levels of these modifications are difficult to quantify, and the mechanisms by which growth-environment factors affect fiber quality are incompletely documented. Mapping fiber quality variations according to fruiting site shows that the fiber properties most closely related to maturity depend on source-boll position on the plant and, thus, on flowering date and the environmental conditions prevailing during maturation of that source-boll. Fiber maturation rates are particularly sensitive to temperature, and strong correlations exist between heat-unit accumulation and maturity-related fiber properties, *i.e.*, circularity, immature fiber fraction, cross-section, and micronaire. Depending on the boll location on a plant and the location of that plant in the field, each boll develops and matures in a slightly different growth micro-environment. These variations in growth environment amplify the natural variability in cotton fiber properties, particularly fiber 'fineness' and maturity. Environment-related variability in fiber cross-sectional shape and maturity persists through fiber processing as problematical variations in yarn evenness, strength, and dye-uptake. These variations in the processed fiber are as directly linked to growth environment as are the accepted relationships between weather and fiber yields. Thus, in the design of environment-responsive management systems for cotton production, it is essential that higher yields *not* be accompanied by increased variability in fiber properties, variability that significantly lowers fiber utility values.

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Introduction

Cotton producers generally assign higher priority to achieving increases in fiber *yield* than to improving fiber *quality*. If the financial return to a cotton producer were based solely on yield, elevating yields, even at the expense of fiber quality, would still result in an acceptable profit. However, cotton fiber-processing success depends on fiber quality, that is, on fiber properties such as length, maturity, and micronaire. Therefore, fiber quality has been made a significant factor in cotton-lint classing and pricing systems. The financial return to a cotton producer is decided *both* by the fiber bulk yield and by how well fiber-property averages meet the fiber-quality requirements of the textile processors and, ultimately, the consumers. If the potentially competing goals of increasing fiber yield and improving fiber-processing quality are to be integrated and achieved, the physiological processes of fiber development must be better understood.

The preceding presentations in this Symposium have dealt with the limitations imposed by the growth environment on physiological processes at the crop, whole-plant, boll, seed, or fiber levels. Metabolic-resource partitioning and, therefore, fiber weight are also modulated or limited by organ, tissue and cell responses to micro-environmental factors. At all organizational levels, cotton physiological responses to micro-environmental variations modulate metabolic rates and metabolic substrate availability. Thus, growth environment governs not only fiber weight-accumulation rates but also fiber-maturation rates and the cell-developmental processes associated with other fiber properties. Growth environment is an important determinant of *both* fiber yield and fiber quality. Thus, the interactions between fiber developmental physiology and variations in the growth environment provide useful and logical linkages for investigations designed to produce more cotton fiber *and* better cotton fiber.

Materials and Methods

For this presentation, data describing the effects of growth-environment factors on cotton fiber yield and quality were drawn from three field studies described elsewhere [Bradow *et al.*, 1996a; Bauer and Bradow, 1996; Bradow *et al.*, 1997]. The experimental designs were: (1) plant mapping of fiber quality X micro-irrigation; (2) fiber maturation rate X environment; and (3) planting date (and annual growth environment) X fiber properties related to yarn-spinning and dye-uptake success.

The plant mapping X micro-irrigation project [Bradow et al., 1996a; Bradow et al., 1997] was part of a subsurface micro-irrigation study of Pee Dee 3 (PD3), an Upland variety grown in Florence SC in 1992 [Camp et al., 1992].

The irrigation treatments were: (1) rainfed (RF, 589 mm total water); (2) in-row (IR, 90 mm additional water applied in nine irrigation events via micro-irrigation tubing buried 0.30 m below the soil surface directly under each row); and (3) alternate-row (AR, 90 mm additional water applied in nine irrigation events via micro-irrigation tubing buried at the same depth as in the IR treatment but between alternate rows). Flowers were tagged at zero days post anthesis. The individual tagged bolls were hand-picked and used in constructing fruiting-site maps of boll weights and roller-ginned fiber properties determined by AFIS (Zellweger-Uster Advanced Fiber Information System) [Bradow et al., 1996a]. Before ginning and AFIS analyses, one boll from branch positions one and two of each node was randomly chosen from each of the four experimental design blocks. Locules from these four-boll sets were pooled so that ten intact, undiseased locules could be randomly selected to represent each fruiting site. One locule was the unit of replication in this study, and each AFIS sample consisted of 10,000 fibers [Bradow et al., 1997].

In the fiber maturation-rate study [Bradow et al., 1996a], Upland genotypes, DES119 and DP5415, and Pima S-6 were grown in Starkville MS in 1992 (DES119 and Pima S-6) or 1993 (DP5415 and Pima S-6). Bolls were harvested at 14, 21, 28, 35, 42, or 56 days post floral anthesis. Bracts and stems were removed from the bolls, and the bolls were cut open and frozen before lint was separated from seed by dissection. All fibers from a single boll (unit of replication) were analyzed together and sequentially by AFIS and Ca-XRF (Wartelle, et al., 1995) AFIS sample sizes ranged from 3,000 fibers from the 21-DPA bolls to 10,000 fibers from the 56-DPA bolls. At 14 DPA, fibers were not sufficiently differentiated for AFIS analyses and were analyzed by Ca-XRF only.

The experimental design of the planting-date study used four Upland cotton genotypes, DP20, DP50, DP90, and DP5690, planted in mid-April (early), early-May (normal), and mid-May (late) in 1991 and 1992 in Florence SC [Bauer and Bradow, 1996]. Equivalent growth-season lengths following each planting date within a year were achieved when harvest dates were similarly staggered in both years. Fiber was spindle-picked before saw-ginning. Fiber-quality properties were determined by AFIS (10,000 fiber sample size) before 50-g subsamples of ginned fiber were spun into 22/1 yarns that were subsequently processed into undyed and blue-dyed knit swatches [Bradow, et al., 1996b].

Most of the data analyses discussed in this presentation were reported and discussed in earlier publications [Bradow et al., 1996a; 1996b; Bauer and Bradow, 1996; Bradow et al., 1997.] In addition to those analyses of variance and regression analyses, relationships between heat-unit accumulation and fiber properties were examined by regression analysis [Johnson et al., 1997; Bradow and Bauer, 1997a; Bradow and Bauer, 1997b].

Results and Discussion

Genotype Responses to Variations in Macro-Environmental Factor [Irrigation Method] Modulated Fiber Quality Levels, Distributions and Variability. Boll frequencies and distributions in the South Carolina plant mapping X micro-irrigation study of 1992 depended on irrigation method (Table 1). Irrigation by either the in-row (IR) or alternate-row (AR) method generally increased the number of second position (P2) bolls on Nodes 12 and below. Early in the flowering period (first branch position, Nodes 6 through 13), IR irrigation delayed flowering by an average of six days. Above Node 13, IR irrigation accelerated flowering in the first position (P1) by an average of five days. The AR boll-distribution pattern was more similar to the pattern found on the rainfed (RF) plants than to the IR boll retention pattern.

The three irrigation methods had no significant effect on total seed cotton yields (Table 2). The IR irrigation seed cotton yield was 96% that of the RF crop; the AR irrigation yield was 104% that of the RF crop. Neither were the fiber yields from the three irrigation treatments significantly different. Independent of irrigation method, 58 to 59% of the yield occurred at P1, and an additional 9 to 11 percent of the yield was produced on each of the outer sympodial branch positions. In all three irrigation treatments, the highest mean boll weights were found at Position 4, independent of node number.

In this randomized complete block design, all PD3 plants experienced the same macro-environment (temperature, insolation, cultural inputs), except for the additional 90 mm of water applied in the IR and AR irrigation treatments. Although irrigation method had no significant effect on yield, irrigation-related differences in boll frequency and distribution (Table 1) were related to variations in fiber-quality properties (Table 3). Irrigation method, node, branch position, and the interactions between irrigation method X node, node X branch position, and irrigation method X node and branch position all were significant factors in determining PD3 fiber length [Bradow et al., 1997].

The 1992 PD3 crop mean fiber length by weight or L[w] was 24.1±2.9 mm (P1 and P2 data pooled across all irrigation treatments). However, the range represented by that crop mean included a minimum L[w] of 6.9 mm for a locule from AR Node 15, P2 and a maximum L[w] of 31.2 mm for an AR Node 14, P2 locule. The AR L[w] mean across branch positions was 24.2±3.3 mm and not significantly different from the crop mean. The IR L[w] range was from 11.9 mm (Node 13, P2) to 30.7 mm (Node 12, P1) with a mean *across branch positions* of 23.5±10.5 mm. The RF mean L[w] after pooling P1 and P2 data was

24.5±2.9 mm with an individual locule L[w] range of 11.9 mm (RF Node 12, P2) to 29.0 mm (RF Node 10, P1). Thus, the extremes of the L[w] ranges occurred within the 'main crop' from Nodes 10 through 15, regardless of irrigation treatment, and the IR treatment increased fiber length variability.

The distributions of P1 fiber-property means, *i.e.*, L[w], Immature Fiber Fraction or IFF, cross-sectional area or A[n], and micronaire, tabulated by node and irrigation treatment are shown in Table 3. Similarly tabulated P2 fiber-property distributions are seen in Table 4. The boll-selection criteria for these AFIS analyses, which were limited to fiber from the first two branch positions of Nodes 7 through 18, introduced a bias toward *higher*-quality bolls, *i.e.*, intact, undiseased, field-opened bolls from a hand-picked crop. Thus, in Tables 3 and 4, the variations in fiber properties correlated with the variations in fruiting site [micro-environment] and irrigation method [macro-environment] should be even greater in the bulk, mechanically picked crop.

Irrigation treatment also varied fiber cross-sectional area, A[n]. Irrigation method, node, branch position, and the interactions of node X irrigation method, irrigation method X branch position, node X branch position, and irrigation method X node X branch position were all significant factors in the A[n] analysis of variance [Bradow et al., 1997]. The 1992 PD3 crop mean for A[n] was 102.19±20.0 μm^2 (P1 and P2 data pooled across all irrigation treatments). The range of locule A[n] represented by that mean was 10.4 μm^2 (IR Node 12, P2) to 145.0 μm^2 (AR Node 7, P1). The RF A[n] mean was 107.1±20.1μm^2 with a range from 41.4 μm^2 (RF Node 11, P2) to 143.4 μm^2 (RF Node 10, P2). The IR A[n] mean was the most variable at 100.2±57.2 μm^2 with a range of 10.4 μm^2 (IR Node 12, P2) to 144.6 μm^2 (IR Node 15, P1). The AR A[n] mean across the two central branch positions was 99.7±20.2 μm^2, and with a range from 45.3 μm^2 (AR Node 10, P2) to 145.0 μm^2 (AR Node 7, P1). Again, the extremes in the fiber property, cross-sectional area, were found *within* the main crop on P1 and P2 of Nodes 7 through 15. The distributions of P1 and P2 A[n] means among fruiting sites and irrigation methods are shown in Tables 3 and 4.

Only one genotype was used in the plant mapping X irrigation study. Therefore, the observed variability in fiber physical properties, such as staple length and A[n] (or fineness), resulted from the physiological responses of a single genotype, PD3, to the interactions between irrigation treatment [macro-environment] and boll position on the plant [micro-environment]. Irrigation method and fruiting site were also significant factors in determining fiber maturity quantified as the degree of fiber secondary-wall thickening (θ) and as micronaire [Bradow et al., 1997].

One useful quantifier of fiber maturity, Immature Fiber Fraction, IFF, is the percentage of fibers for which $\theta < 0.250$, where $\theta = 1.000$ for a perfect circle and θ for mature Upland fibers is larger than 0.500. The 1992 PD3 crop mean IFF was 15.3±9.7% (P1 and P2 data pooled across irrigation treatments). The highest locule IFF (locule with the most immature fiber) was found in an RF locule (75.0% at Node 14, P1). The lowest locule IFF, 2.5%, also occurred in an RF locule (Node 10, P2). The RF mean IFF was 12.9±9.2% across both branch positions and Nodes 7 through 18. The IFF mean for the IR irrigation treatment was 16.8±25.3%; and the IR maximum IFF was 63.1% (Node 8, P2) with a corresponding minimum of 3.5% at IR Node 15, P1. The AR mean IFF was 16.2±9.1% with a maximum of 58.1% (AR Node 15, P2) and minimum of 3.6% (AR Node 8, P1). The distributions of IFF according node and branch position are shown in Tables 3 and 4.

Significant fiber-maturity effects from the three irrigation treatments were also seen in the micronaire (micronAFIS) means. Like θ and the IFF distribution function of θ, micronaire was significantly modified by interactions between irrigation treatments, node number and branch position [Bradow et al., 1997]. In 1992, the PD3 crop mean micronaire was 3.84±1.34. That crop mean represented a range from 0.13 (RF locule at Node 15, P1) to 7.19 (RF locule at Node 7, P1). The RF micronaire mean of 4.36±1.26 was the highest of the three irrigation treatment means. The IR micronaire mean was 3.61±2.78 with a range from 0.21 (IR Node 8, P2) to 6.59 (IR Node 15, P1). The AR micronaire mean was 3.58±1.39 with a range of 0.23 (AR Node 10, P2) to 7.10 (AR Node 7, P1). *All* irrigation treatments and *all* fruiting sites produced locules containing fiber with micronaire readings outside the acceptable 3.5 to 4.9 micronaire range. The environment-related variations in micronaire also resulted in micronaire *means* at fruiting sites that were outside the 3.5 to 4.9 micronaire range (Tables 3 and 4). The P2 micronaire means from the IR and AR irrigation treatments were below 3.5, as was the P2 crop micronaire mean (Table 4). The IR irrigation treatment resulted in the highest variability in micronaire.

The data discussed above and presented in Tables 1 through 4 contrast the ways in which growth environment affects fiber yield and fiber quality. One macro-environment factor, irrigation method, had no significant effect on yield or on the relative contributions of fruiting sites to the total yield. Irrigation method, however, did alter flowering dates and, consequently, the distribution of bolls among the fruiting sites. Each fruiting site on a cotton plant represents a variation in micro-environment, and the offsets in flowering date related to irrigation method amplified the natural variations in the fruiting-site micro-environments in which the individual bolls developed. Since the IR irrigation method delayed flowering at Nodes 13 and below by an average of six days, an RF boll at Node 8, P1 developed in a 'earlier-season'

micro-environment than did a boll produced at the same IR node and position.

Flowering Date and Boll Micro-Environment Modulated Fiber Maturation Rates and Fiber Property Variability. Flowering dates determine the thermal micro-environment in which each boll develops, and temperature is a significant metabolic-control factor. Therefore, it follows that fiber developmental rates should differ in bolls from the July 28 and August 19 flowering dates in the fiber maturation rate X environment study [Bradow et al., 1996a; Bradow et al., 1996c]. That study included two Upland cotton genotypes, DES119 in 1992 and DP5415 in 1993 and a *Gossypium barbadense* genotype, Pima S-6, planted in both years of the study. Bolls were harvested at 21, 28, 35, 42, or 56 days post floral anthesis, and regression analyses were used to determine fiber developmental rates based on AFIS fiber properties. In Table 5, fiber elongation and maturation rates are compared on the bases of genotype and flowering date. (No bolls from August flowers were collected in 1992. The Pima S-6 and DES119 data from that year were included to provide comparisons between additional genotypes and crop-year environments.) Also shown in Table 5 are fiber secondary wall filling rates based on primary cell wall dilution rates from 14 to 56 DPA determined by Ca-XRF [Wartelle, et al., 1995].

In 1993, fiber elongation rates for the August-flower bolls were twice those for the July-flower bolls of both DP5415 and Pima S-6 (Table 5). Fiber elongation rates for the 1992 July-flower bolls were higher than those for the 1993 July-flower bolls of both species. A comparatively cool spring in 1992 significantly retarded early-season fiber development so that fiber elongation continued beyond 28 days post anthesis. At harvest, 56 days post anthesis, the 1992 DES119 and Pima S-6 mean fiber lengths were not significantly different from the lengths expected for Upland and Pima genotypes, respectively. At harvest in 1993, fiber lengths in the July-flower bolls and August-flower bolls were not significantly different. In both instances, increasing thermal input as the growing season progressed accelerated the rate at which cotton fibers elongated to genetically determined lengths.

This same thermal effect was seen in fiber-maturation rates quantified as decreasing Immature Fiber Fractions (IFF). Maturation rates of the July-flower bolls of both DP5415 and Pima S-6 were lower than those of August-flower bolls. The maturation rates based on 1992 July-flower IFF were closer to those of 1993 August-flower bolls than to the rates observed for 1993 July-flower bolls. The micronaire of both Upland genotypes increased at the same rate for the July-flower bolls, and the micronaire-based maturation rate was accelerated in the August-flower bolls of DP5415.

The August-flower Pima S-6 fibers increased in micronaire at the slowest rate of any of the genotype X year X flowering date combinations examined. This study was conducted in Starkville MS where normal growing-season lengths and heat-unit accumulations are not fully appropriate for Pima genotypes, and the failure of August-flower Pima S-6 fibers to increase in micronaire at the same rate and to the same extent as fibers from the earlier flowers was related to the growth-environment requirements of Pima genotypes. Genotype-related differences in fiber fineness, more so than environmental effects, determined the rates at which Upland and Pima fiber cross-sectional areas, A[n], increased over time. The Upland DP5415 fibers increased in cross-sectional area more rapidly than did the Pima S-6 fibers. Genotype thermal and season-length requirements of *G. barbadense* significantly decreased the rate at which August-flower Pima S-6 A[n] increased.

Thermal-environment effects also interacted with genotype in determining the rates of cell wall deposition. The Ca-XRF primary-wall dilution assay, which quantifies fiber calcium content by weight, was used to follow fiber wall deposition and fiber maturation as the calcium-rich primary cell wall was diluted by addition of highly cellulosic secondary wall components [Wartelle, et al., 1995]. Thus, the higher a fiber-sample calcium concentration was, the less mature were the fibers. Based on the Ca-XRF assay, August-flower DP5415 fibers matured more rapidly than did the corresponding July-flower fibers. The relatively cool spring in 1992 resulted in more rapid 'season-total' maturation rates for both DES119 and Pima S-6. The suboptimal environment experienced by the 1993 August-bloom Pima S-6 bolls interfered with cellulose deposition in the secondary walls of the fibers in those bolls, and the increased variability in fiber properties resulted in the minimally positive slope seen in Table 5.

Thermal Environment Interacted with Day-Length and Insolation in Modulating Fiber Maturation Rates. Genotype characteristics, expressed as fiber length and fineness or as genotype-related responses to growth environment, were significant factors in this fiber maturation rate X environment study. However, growth environment, particularly temperature, also affected fiber elongation, maturation, and fiber-wall thickening. When fiber developmental rates were calculated on the basis of heat-unit accumulation, close linear relationships were found between fiber maturation rates and cumulative Growth Degree Days (GDD). Four different heat-unit accumulation models have been explored and compared (Johnson et al., 1997). Based on the correlation coefficients between AFIS fiber properties and GDD calculated by the individual models, three GDD models were found to be relatively effective. Table 6 shows the linear regression slopes, correlation coefficients, and significance levels obtained with the model: GDD4 = $\sum(T_{max} - T_{base})$ where $T_{base} = 13.5^{\circ}C$. If T_{max} exceeded $T_{ceiling} = 32.0^{\circ}C$, then T_{max} adjusted to $T_{ceiling}$.

On the basis of heat-unit accumulations, there was no inter-species difference in fiber elongation, L[w]. The slopes of all GDD4 X L[w] linear regressions were the same, *i.e.*, +0.0004 mm per Growth Degree Day (Table 6). Immature Fiber Fraction for both Upland and Pima genotypes decreased at the same rate (-0.07 percent per GDD). However, the cross-sectional area of the finer Pima fibers increased at half the rate of the coarser Upland genotypes. This genotype or species difference in fiber fineness was also seen in the rate of micronaire increase and the rate of secondary wall deposition quantified by Ca-XRF.

These linear relationships between fiber properties and cumulative heat units depended on only one environmental factor, temperature. When day-length was included in the model, the GDD4 + GDD4*D(ay-length) model described more than 50% of the variation in fiber length for both the Upland and the Pima genotypes (Table 7). Inclusion of insolation in the heat-unit model had no effect on the success of the L[w] model, but GDD4 + GDD4*D + GDD4*R(adiation, solar) described more than 65% of the variation in fiber length when the two species were considered separately.

The heat unit X day-length X radiation model was also highly successful in describing the Immature Fiber Fraction of the two species ($r^2 \geq 0.79$) The multiple-regression models did not improve prediction of A[n] or micronaire, and the marked species difference in fiber fineness made inappropriate the pooling of data across species.

Planting Date and Micro-Environment Interacted to Modulate Fiber Maturation Rates and Fiber Property Variability. Temperature, of course, was not the only environmental factor determining cell morphology, and thereby, fiber quality in the fiber maturation rate X environment study just discussed. Temperature and cumulative heat units were, however, the major environmental factors when rainfall and insolation were adequate and evenly distributed during the fruiting period in 1992 and 1993 in Mississippi. This was not the case in the plant mapping study from South Carolina in 1992 when an early-season drought and excessive rainfall during the flowering period inhibited seed and fiber development. Indeed, 1992 was a very poor year to have grown cotton in South Carolina. This was quite evident in the markedly reduced 1992 yields in the South Carolina planting-date study [Bauer and Bradow, 1996].

The South Carolina planting-date X environment study of DP20, DP50, DP90, and DP5690 was begun in 1991 and continued in 1992, overlapping the plant mapping X irrigation study of PD3 discussed above. The staggered planting and harvest dates, as well as cumulative heat-unit data are shown in Table 8. Differences in the 1991 and 1992 growth environments resulted in significant differences in fiber yields from all four genotypes (Table 9). The 1991 and 1992 growth environments and genotype responses to the environment also significantly modulated the fiber properties of all four genotypes (Bradow and Bauer, 1997). The yields from all genotypes were significantly higher in 1991, which was the hotter, drier, shorter growing season if only environmental-factor *totals* are considered (Table 8). The influences of planting date and micro-environment, were particularly evident in those fiber properties most closely related to fiber maturity (Table 10), including micronaire (Table 11). In 1991 all micronaire means were within the 3.5 to 4.9 non-penalty micronaire limits. However, DP5690 micronaire readings from all three planting dates in 1992 equaled or exceeded 4.9, as did the 1992 DP50 micronaire from the early planting date. Thus, the higher 1991 yields were correlated with lower micronaire in all four genotypes (Table 11).

There were also significant differences among the Immature Fiber Fractions (Table 12). The 'earliest' genotype, DP20, had by far the largest IFF means in 1991, a genotype-specific effect which was not repeated in the longer, cooler growing season of 1992. Regardless of planting date, 1992 IFF percentages for DP20 and DP50 were lower than or equal to the corresponding IFF values in 1991. The same relationship between 1991 and 1992 IFF percentages of the longer-season genotypes, DP90 and DP5690, was seen in the early and late plantings only.

A possible basis for these effects of crop year on IFF and micronaire is seen in Table 8 where the season totals define 1991 as the shorter, drier, hotter year. However, when the two seasons were considered in 50-day increments, the 1991 and 1992 thermal environments differed only in the significantly higher heat-unit (Degree Day 16°C or DD16) accumulations in the first 50 days after planting in 1991. When the effects on fiber maturity of the thermal environments within those 50-day growth-season increments were compared as separate regressions of IFF on the three different DD16 accumulations associated with the staggered planting dates, the fiber maturation rates (linear regression slopes) in Table 13 were obtained. In 1991, the fiber maturation rate over all genotypes was -0.030 IFF % per DD16 heat-unit. In 1992, IFF decreased 0.020 percentage points per DD16 heat-unit. When the heat-unit accumulations during the first 50 days after planting were considered separately, the slope of the 1991 IFF vs DD16 regression was +0.009, compared to +0.005 in 1992.

The inverse relationship shown in Table 13 between fiber maturity and heat-unit accumulation during the first 100 days after planting was observed for all four genotypes and in both years. Since the 50-DAP and 50 to 100 DAP periods corresponded roughly to pre-flowering and main-bloom stages, respectively, it appears that the higher heat-unit accumulations early in 1991 resulted in heavier boll loads. During the 100 days before cutout, the larger 1991 boll population created greater demands and competition

for the metabolic resources needed for seed and fiber maturation. The amplified competition for metabolic resources in 1991 would have increased the ratio of immature fiber, particularly in DP20, the most early maturing of the four Upland genotypes. Because DP20 matures earlier in the season, heat-unit accumulations after 100 DAP would have a smaller effect on DP20 fiber maturity than upon the maturation rates of the slower maturing genotypes in this study. Early planting ameliorated some of this effect (Table 12), but high DP20 yields in 1991 (Table 9) were associated with elevated IFF percentages. Further discussion of the effects of heat-unit accumulations upon fiber maturity properties can be found elsewhere in these *Proceedings* [Bradow and Bauer, 1997a].

Environment-Related Modulations of Fiber Properties Persisted Through Processing as Modifications of Yarn and Undyed and Dyed Fabric Characteristics. When the importance of temperature in governing the rates of biochemical and metabolic processes is considered, these correlations between fiber maturation rates and thermal micro-environment are seen as logical extensions of cell metabolic and enzyme kinetics. That environmentally induced modulations in cell metabolism should translate into differences in yield (cell weight) also follows from the many studies of both plant cell metabolism and cotton production research. However, the close relationships between variability in fiber quality, as defined and demanded by the textile industry, and variations in micro-environments during the growing season are less easily perceived and understood.

The differences in fiber maturity which were correlated with thermal environment (cumulative DD16) and shown in Table 13 persisted through fiber processing as 'planting date' and 'year' effects in the yarn properties discussed by Bradow and Bauer elsewhere in these *Proceedings* [1997a ; 1997b]. The results of the three-way analyses of variance in yarn-property data with planting date, year, and genotype as the main effects are shown in Table 14. Genotype was highly significant in all analyses and that column was omitted to save space. The planting-date effects in Table 14 can be related to cumulative heat units just as variations in IFF were in Table 13. In Table 15, yarn elongation percent increased with increasing cumulative heat units and independently of 50-day growth-season increment. Yarn breaking strength and breaking tenacity improved with increasing heat-unit accumulations during the flowering period between 50 and 100 days after planting.

The effects of fiber maturity and cumulative heat units on *undyed* fiber color are discussed elsewhere in these *Proceedings* [Bradow and Bauer, 1997b]. Increasing heat accumulations consistently increased the whiteness and decreased the 'yellowness' of undyed cotton fiber. Genotype modified the 'lightness' of color in blue-dyed fiber, and year had no effect. However, the early-season heat unit accumulations that contributed to decreased fiber maturity also resulted in a lighter color in the dyed fiber (more positive +L in Table 16). The blue color component, -b, is a negative number, and increasing heat-unit accumulations resulted in a deeper, 'truer' blue even though the color was lighter (more positive +L).

Environmental factors that alter the population size of immature fiber and modify the rate at which cotton fiber matures primarily affect the degree of development reached by the secondary wall before crop termination and harvest. Immature fibers have thinner, more elastic walls that collapse more completely into the cell lumen space during desiccation after boll-opening. These flatter, less mature fibers are also more elastic, and immature fibers are less likely than fully mature fibers to break during fiber processing. However, the higher elasticity of the immature fibers also increases the probabilities of stretching under tension and snarling when tension is released as the fiber moves through ginning and spinning processes. Thus, the existence of higher ratios of immature fiber within a crop is directly related to higher frequencies of yarn neppiness and unevenness.

Limited cellulosic wall deposition in the immature fibers is even more important in determining dye uptake success. Since most cotton dyes are formulated to dye the main component of the fiber, cellulose, the lower amounts of cellulose in the immature fibers result in decreased dye uptake and, hence, *lighter* colors. The color of dyed immature fibers may be 'truer' since a flatter, more collapsed fiber reflects and reflects light more directly than do the more rounded mature fibers. The human eye, however, more easily perceives the lighter color and higher reflectance. Thus, 'white' specks among dyed fibers are more precisely dyed fiber aggregates that contain 'lighter', less mature fibers.

Summary

A cotton producer's financial survival depends most directly (and obviously) on the number of pounds of fiber produced per acre. Therefore, it is not surprising that *increased yield* has been and remains the *primary* goal of efforts to improve cotton-production management and genotype responses to unavoidable variations in the growth environment. However, the 'average' cotton field inevitably encompasses quantifiable and significant variations in soil drainage, fertility and type. Thus, every cotton plant and each boll on a plant in an 'average' field grows in a slightly different micro-environment.

Mechanisms by which growth environment modulates fiber yield and weight can best be discerned at the individual seed and fiber levels. Did the growth environment inhibit fiber elongation so that subsequent deposition of cellulose in the secondary wall resulted in short, thick, brittle fibers?

Were too many bolls set or metabolic resources too limited for a fully mature fibers to be produced on all of the seeds? Did late-season bolls that developed in the less favorable micro-environments produce less mature fiber? Were increases in the *quantity* of fiber gained at the expense of those *qualities* of cotton fiber that are most important to the processors?

Fiber yield is a cumulative weight function that depends on multiple interactive growth-environment factors, but fiber quality, as defined by the processors, is a composite of several inherently variable fiber characteristics that are significantly modified by the micro-environments in which the individual fibers are produced. During cotton classing and pricing, components of the fiber-quality composite are treated as averages, *e.g.*, bale-average micronaire, staple length, or maturity index. However, the spinning and dye-uptake properties of cotton fibers are determined by the continua of individual fiber characteristics within those fiber-quality averages. Thus, it is possible to increase yield [total fiber weight] and to improve *average* fiber quality while increasing the variability of the individual fiber properties and, thus, decreasing processing-success potential.

Achievement of a viable balance between 'fiber quantity' and 'fiber quality' must be a significant element in cotton breeding programs intended to optimize cotton production in variable growth environments. Selection for quantity, without sacrificing quality, is also an essential component in the design of environment-responsive management systems that maximize yields of cotton fiber that meets processing 'fiber quality' requirements.

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Table 1. Effects of irrigation method on boll distributions on PD3 plants from 1-m rows with four replicates.

Irrigation Method	Branch Number	Number of Bolls at Branch Position:				
		1	2	3	4	5
Rainfed		1				
In-row	5					
Alt-row						
Rainfed		1	2	1		
In-row	6	1				
Alt-row		4	1	1		
Rainfed		5	4			
In-row	7	6	2	1	1	
Alt-row		5	4	1		
Rainfed		10	5	3		
In-row	8	10	11	6	1	1
Alt-row		9	10	3		
Rainfed		13	9	2	2	
In-row	9	12	11	**3**	1	
Alt-row		12	8	2		
Rainfed		16	9	2		
In-row	10	18	13	4	**3**	
Alt-row		16	11	1	2	
Rainfed		21	6	4	1	
In-row	11	17	7	4		
Alt-row		18	11	3		1
Rainfed		19	5	2		
In-row	12	19	18	1		1
Alt-row		22	7	3		
Rainfed		17	5			
In-row	13	14	7	2		
Alt-row		19	3		1	
Rainfed		12	4	2		
In-row	14	10	1	1		
Alt-row		16	4		1	
Rainfed		7	1	1		
In-row	15	10	3	1		
Alt-row		12	1	2	1	
Rainfed		8	1	1		
In-row	16	6	3			
Alt-row		11	2			
Rainfed		4				
In-row	17	6				
Alt-row		8	1			
Rainfed		3				
In-row	18	5	1			
Alt-row		8	1			
Rainfed		2				
In-row	19	1				
Alt-row		6	2			
Rainfed		2				
In-row	20	2				
Alt-row		3	1			
Rainfed						
In-row	21	1				
Alt-row		1				
Rainfed						
In-row	22	1				
Alt-row		1				

Table 2. Effects of irrigation method on seed cotton weights of PD3.

Irrigation Method	Branch Number	Boll Mean Weight [g] at Branch Position:				
		1	2	3	4	5
Rainfed		6.3				
In-row	5					
Alt-row						
Rainfed		5.2	5.5	3.9		
In-row	6	2.5				
Alt-row		4.9	3.4	3.3		
Rainfed		5.0	4.5			
In-row	7	4.1	5.4	4.8	5.6	
Alt-row		4.6	3.6	2.2		
Rainfed		5.1	6.7	6.1		
In-row	8	2.7	5.5	4.8	6.4	5.1
Alt-row		4.9	4.5	3.4		
Rainfed		5.8	5.3	4.5	4.9	
In-row	9	5.1	2.2	5.1	1.6	
Alt-row		5.7	5.6	4.4		
Rainfed		5.6	5.3	6.6		
In-row	10	2.8	4.5	5.1	3.9	
Alt-row		5.7	4.1	4.6	4.1	
Rainfed		6.2	7.1	6.1	6.5	
In-row	11	6.1	5.1	3.8		
Alt-row		5.6	5.0	4.3		2.0
Rainfed		6.4	5.4	1.4		
In-row	12	5.7	4.9	5.4		5.7
Alt-row		5.8	5.5	4.1		
Rainfed		6.9	5.0			
In-row	13	5.6	5.0	2.8		
Alt-row		5.5	3.1		2.7	
Rainfed		6.1	5.8	5.4		
In-row	14	5.0	5.5	6.3		
Alt-row		6.1	4.7		2.7	
Rainfed		6.4	3.1	6.1		
In-row	15	5.1	5.8	7.0		
Alt-row		5.0	7.0	6.4	6.6	
Rainfed		6.8	4.9	4.6		
In-row	16	5.9	4.7			
Alt-row		4.7	3.6			
Rainfed		7..2				
In-row	17	6.7				
Alt-row		4.5	4.4			
Rainfed		3.5				
In-row	18	5.8	5.6			
Alt-row		4.3	4.6			
Rainfed		5.7				
In-row	19	6.2				
Alt-row		5.1	5.2			
Rainfed		6.0				
In-row	20	5.2				
Alt-row		3.8	4.8			
Rainfed						
In-row	21	6.0				
Alt-row		5.5				
Rainfed						
In-row	22	3.9				
Alt-row		7.6				

Table 3. Effects of irrigation method on first position (P1) fiber quality property means of PD3. [Length by weight , L[w], Immature Fiber Fraction, IFF, cross-sectional area, A[n], and micronaire , micronAFIS, for sympodial branches 7 through 18 only.] (Means of 10 locules)

Irrigation Method	Branch Number	Mean Fiber Quality Property [P1]			
		L[w] mm	IFF %	A[n] μm^2	Micronaire micronAFIS
Rainfed	7	25.6	4.5	135.0	6.52**
In-row		25.9	10.9	104.1	4.10
Alt-row		24.7	18.4	106.6	3.96
Rainfed	8	21.8	20.5	90.7	2.88
In-row		23.9	16.5	99.9	3.85
Alt-row		26.4	9.5	130.6	5.57**
Rainfed	9	24.9	8.5	124.3	5.36**
In-row		22.3	26.4	88.5	2.28*
Alt-row		27.5	12.7	93.3	3.57
Rainfed	10	24.7	11.4	114.2	4.67
In-row		25.9	19.6	99.1	3.75
Alt-row		24.7	13.3	102.0	4.09
Rainfed	11	26.3	11.5	106.2	4.36
In-row		21.9	20.2	108.9	3.57
Alt-row		24.9	12.3	111.7	4.45
Rainfed	12	23.7	14.0	111.1	4.46
In-row		27.2	6.2	107.7	5.21**
Alt-row		24.5	19.1	106.0	3.61
Rainfed	13	25.4	13.1	101.1	4.00
In-row		17.6	30.6	102.2	2.42*
Alt-row		25.4	14.1	101.0	3.99
Rainfed	14	21.4	27.8	83.2	2.50*
In-row		21.2	13.3	102.3	3.76
Alt-row		--	---	---	---
Rainfed	15	25.6	19.5	94.3	3.58
In-row		24.5	7.9	121.7	5.21**
Alt-row		22.5	12.0	102.6	4.12
Rainfed	16	28.3	11.4	109.0	4.47
In-row		22.3	13.5	109.0	4.23
Alt-row		23.5	21.1	79.6	2.60*
Rainfed	17	22.9	7.1	127.3	5.44**
In-row		26.5	11.0	104.0	3.97
Alt-row		---	---	---	---
Rainfed	18	23.4	9.0	114.3	4.57
In-row		21.5	23.7	78.8	2.40*
Alt-row		22.0	13.9	99.0	3.40*
Crop Mean ± s.d.		22.8 ±2.4	14.9 ±2.5	105.0 ±13.0	4.03 ±0.97
Rainfed Mean ± s..d.		24.5 ±1.9	13.2 ±6.8	109.2 ±15.8	4.40 ±1.2
In-row Mean ± s..d.		23.4 ±2.7	16.7 ±7.7	103.8 ±8.4	3.79 ±0.96
Alt-row Mean ± s.d.		24.6 ±1.6	14.7 ±3.4	103.2 ±12.3	3.93 ±0.73

* Below 3.5 micronaire penalty limit; ** Above 4.9 micronaire penalty limit.

Table 4. Effects of irrigation method on second position (P2) fiber quality property mean of PD3. [Length by weight , L[w], Immature Fiber Fraction, IFF, cross-sectional area, A[n], and micronaire , micronAFIS, for sympodial branches 7 through 18 only.] (Means of 10 locules.)

Irrigation Method	Branch Number	Mean Fiber Quality Property [P2]			
		L[w] mm	IFF %	A[n] μm^2	Micronaire micronAFIS
Rainfed	7	25.9	9.3	99.9	4.23
In-row		26.1	13.7	98.7	3.70
Alt-row		25.2	9.6	71.3	2.21*
Rainfed	8	25.5	10.5	105.8	4.51
In-row		22.7	36.1	83.7	2.18*
Alt-row		24.6	11.3	90.9	2.20*
Rainfed	9	26.7	8.2	117.7	5.18**
In-row		17.6	18.1	104.6	3.36*
Alt-row		27.5	14.0	92.6	3.62
Rainfed	10	23.2	14.3	119.5	4.59
In-row		23.1	12.5	101.7	3.78
Alt-row		26.4	19.5	82.4	2.98*
Rainfed	11	26.3	9.4	103.7	4.62
In-row		24.3	12.9	101.9	3.89
Alt-row		22.5	20.3	95.4	3.05*
Rainfed	12	22.7	21.6	95.2	3.18*
In-row		23.9	12.3	92.3	3.67
Alt-row		25.1	8.7	120.0	4.95**
Rainfed	13	22.4	12.3	106.6	3.97
In-row		21.7	20.7	90.2	2.57*
Alt-row		22.0	19.44	79.6	2.31*
Rainfed	14	23.6	13.3	108.3	3.89
In-row		---	---	---	---
Alt-row		23.0	14.3	114.5	3.93
Rainfed	15	---	---	---	---
In-row		26.7	13.9	94.8	3.42*
Alt-row		19.1	23.3	95.2	2.58*
Rainfed	16	---	---	---	---
In-row		---	---	---	--
Alt-row		---	---	---	----
Rainfed	17	---	---	---	---
In-row		---	---	---	---
Alt-row		19.8	22.0	99.4	2.73*
Rainfed	18	---	---	---	---
In-row		---	---	---	---
Alt-row		---	---	---	---
Crop Mean ±s.d.		23.7 ±2.4	15.7 ±2.5	93.2 ±23.2	3.38* ±1.07
Rainfed Mean ± s.d.		24.5 ±1.61	12.3 ±4.0	100.8 ±19.4	4.27 ±0.56
In-row Mean ± s.d.		23.3 ±2.6	17.5 ±7.6	96.0 ±6.6	3.32* ±0.58
Alt-row Mean ± s.d.		23.5 ±2.6	16.8 ±7.1	85.58± 30.2	2.78* ±1.19

* Below 3.5 micronaire penalty limit; ** Above 4.9 micronaire penalty limit.

Table 5. Effects of micro-environment (flowering date) on fiber maturation rates of DP5415 and Pima S-6. (Regression analyses over 21 to 56 days post anthesis, n = 6).

Geno-type	Fiber Maturation Rate (Linear Regression Slope over time)				
	Flower-ing Date	L[w] mm/d	IFF %/d	A[n] μm^2/d	Micro-naire unit/d
DP5415	7/28/93	+0.002	-0.898	+1.476	+0.124
DP5415	8/19/93	+0.005	-1.466	+1.547	+0.140
DES119	7/22/92	+0.011	-1.434	+1.089	+0.125
Pima S-6	7/22/92	+0.009	-1.492	+0.761	+0.108
Pima S-6	7/28/93	+0.004	-1.043	+0.929	+0.100
Pima S-6	8/19/93	+0.008	-1.492	+0.302	+0.078

Rate of Secondary Wall Deposition quantified as Primary Wall Dilution Effect by Ca-XRF (Wartelle, et al., 1995).

		mg Ca/ kg-d
DP5415	7/28/93	-15.13
DP5415	8/19/93	-19.67
DES119	7/22/92	-41.41
Pima S-6	7/22/92	-24.97
Pima S-6	7/28/93	-6.78
Pima S-6	8/19/93	+3.37

Table 6. Correlations between cotton fiber quality and heat-unit (Degree Day, DD16) accumulation. Model : GDD4 = $\sum(T_{max} - T_{base})$ if $T_{max} > T_{ceiling}$, then T_{max} = ceiling. T_{base} = 13.5 C; $T_{ceiling}$ = 32 C. See Johnson et al., 1997.

Genotype	Fiber Maturation Rates (Linear Regression Slopes and r^2 from GDD4 Heat-Unit Accumulation Model)			
	L[w] mm/DD16	IFF %/DD16	A[n] μm^2/DD16	Micronaire Unit/DD16
Upland DP5415 + DES119	+0.0004 0.30 ****	-0.0700 0.69 ****	+0.0827 0.69 ****	+0.0077 0.77 ****
Pima S-6 (Pooled)	+0.0004 0.44 ****	-0.0716 0.68 ****	+0.039 0.43 ****	+0.0050 0.68 ****
All Genotypes Pooled	+0.0004 0.32 ****	-0.0707 0.67 ****	+0.0604 0.34 ****	+0.0065 0.64 ****

Rate of Secondary Wall Deposition (mg Ca/kg-DD16)

Upland DP5415 + DES119	-1.830 0.76 ****	*. **, ***, ****: P < 0.05, 0.01, 0.001, or 0.0001.
Pima S-6 (Pooled)	-0.893 0.31 ****	
All Genotypes Pooled	-1.310 0.53 ****	

Table 7. Increased linear regression coefficients of determination resulting from inclusion of day-length and insolation in fiber quality models based on cumulative heat units. GDD4: Heat Units Only; GDD4+ GDD4*D: Cumulative heat units and day-lengths; GDD4+GDD4*R: Cumulative heat units and radiation; GDD4+GDD4*R+GDD4*D: Cumulative heat units, insolation, and day-lengths.

Model	Multiple Regression Coefficient of Determination, r^2			
	L[w]	IFF	A[n]	Micronaire
Pooled Upland DP5415 and DES119, All Years, All Flowering Dates				
GDD4	0.30	0.69	0.69	0.77
GDD4+ GDD4*D	0.54	0.72	**0.71**	0.79
GDD4+ GDD4*R	0.30	0.71	0.69	0.77
GDD4+ GDD4*R+ GDD4*D	**0.69**	**0.80**	**0.71**	**0.82**
Pooled Pima S-6, All Years, All Flowering Dates				
GDD4	0.44	0.68	0.43	0.68
GDD4+ GDD4*D	0.57	0.71	0.44	0.68
GDD4+ GDD4*R	0.44	0.70	**0.49**	0.71
GDD4+ GDD4*R+ GDD4*D	**0.66**	**0.79**	**0.49**	**0.74**
Pooled, All Genotypes, All Years, All Flowering Dates				
GDD4	0.32	0.67	0.34	0.64
GDD4+ GDD4*D	0.48	0.69	0.35	0.66
GDD4+ GDD4*R	0.32	0.68	0.34	0.65
GDD4+ GDD4*R+ GDD4*D	**0.57**	**0.77**	**0.36**	**0.69**

Table 8. Environmental factors modifying DP20, DP50, DP90, and DP5690 fiber properties in 1991/1992 South Carolina planting date study.

Environmental Parameter	Year	
	1991	1992
Planting Dates	4/17 (early) 5/1 (normal) 5/15 (late)	4/15 (early) 4/29 (normal) 5/15 (late)
Harvest Dates	9/17 9/23 10/10	9/28 10/19 10/30
Season Lengths (Days After Planting, DAP)	155 145 149	167 174 170
Total Rainfall	60.0 cm	89.8 cm
Mean Total Heat Units, Degree-Day-16 [DD16]	1588.8	1352.7
DD16 Heat Units Accumulated by 50 DAP	345.8 430.6 495.3	183.8 237.9 362.9
DD16 Heat Units Accumulated Between 50 and 100 DAP	553.1 600.6 586.4	528.3 595.0 598.6
DD16 Heat Units Accumulated Between 100 and 150 DAP	587.0 431.9 350.9	640.6 484.5 331.9

Table 9. 1991 and 1992 Yields of DP20, DP50, DP90, and DP5415 from Florence SC. (From Bauer and Bradow, 1996; LSD = 148)

	Yield, kg ha^{-1}		
Genotype	Planting Date	1991	1992
DP20	Early Normal Late	1204 1207 1415	500 527 480
DP50	Early Normal Late	1214 1308 1394	527 526 576
DP90	Early Normal Late	1372 1437 1467	496 584 707
DP5690	Early Normal Late	1529 1391 1493	490 730 764

Table 10. Significant separate and interactive effects of genotype, planting date and crop year on fiber maturity. (Three-way analyses of variance, Genotype X Planting Date X Year).

Fiber Property	Mean Square and Significance Level			
	Plant Date	Year	Geno-type X Year	Plant Date X Year
θ	0.003 ****	0.017 ****	0.001 **	ns
IFF	21.69 ****	27.31 ****	7.13 **	ns
A[n]	178.6 ****	295.6 ****	ns	75.3 **
FFF	20.00 ***	13.24 **	ns	10.10 **
micron-AFIS	0.87 ****	2.95 ****	0.24 **	0.19 *

ns = $p > 0.1$; *, **, ***, **** indicate $p < 0.1$, 0.05, 0.01, and 0.001 respectively.

Table 11. 1991 and 1992 micronaire means of DP20, DP50, DP90, and DP5415 from Florence SC.

Genotype	Micronaire (micronAFIS)		
	Planting Date	1991	1992
DP20	Early Normal Late	4.15 3.84 3.68	4.75 4.42 4.32
DP50	Early Normal Late	4.56 4.54 4.04	4.78 4.74 4.68
DP90	Early Normal Late	4.73 4.68 4.37	4.94 4.60 4.58
DP5690	Early Normal Late	4.66 4.85 4.39	5.02 4.94 4.93

Table 12. 1991 and 1992 immature fiber fraction (IFF) means of DP20, DP50, DP90, and DP5415 from Florence SC.

Genotype	IFF, %		
	Planting Date	1991	1992
DP20	Early Normal Late	14.9 15.3 15.9	11.4 12.8 14.3
DP50	Early Normal Late	11.3 11.2 13.9	10.8 11.2 11.2
DP90	Early Normal Late	11.4 12.0 13.2	10.7 12.6 13.1
DP5690	Early Normal Late	11.7 10.2 12.5	10.3 11.2 11.1

Table 13. Comparison of fiber maturation rates [based on IFF] of four cotton genotypes in 1991 and 1992.

Genotype Year	Maturation rate [slope of IFF vs. DD16] Cumulative DD16			
	0-50 DAP	50-100 DAP	100-150 DAP	0 DAP-Harvest
DP 20 1991	+0.007	+0.005	-0.004	-0.019
DP 50 1991	+0.017	+0.012	-0.010	-0.052
DP 90 1991	+0.012	+0.009	-0.007	-0.035
DP 5690 1991	+0.004	+0.001	-0.002	-0.019
DP 20 1992	+0.012	+0.010	-0.008	-0.043
DP 50 1992	+0.006	+0.004	-0.003	-0.017
DP 90 1992	+0.012	+0.010	-0.008	-0.041
DP 5690 1992	+0.005	+0.004	-0.003	-0.018

Table 14. Significant separate and interactive effects on yarn properties of genotype, planting date and crop year on fiber maturity. (Three-way analyses of variance, Genotype X Planting Date X Year).

Yarn Property	Mean Square and Significance Level			
	Plant Date	Year	Geno-type X Year	Plant Date X Year
Neps	ns	***	ns	***
CV%	*	***	ns	ns
Break Strength	**	ns	ns	ns
Elong -ation, %	****	****	ns	ns
Break Tenacity	**	**	ns	ns

ns = p > 0.1; *, **, ***, **** indicate p < 0.1, 0.05, 0.01, and 0.001 respectively.

Table 15. Relationships between yarn properties and heat-unit [DD16 accumulations at 50 and 100 days after planting [DAP] and at harvest. [1991 and 1992 data pooled for four genotypes, DP20, DP50, DP90, and DP5690.]

Yarn Property	Slopes of DD16 versus Yarn Property Regressions and Regression s Equation Significance		
	0 to 50 DAP	50 to 100 DAP	At Harvest > 150 DAP
Nep Count	-0.033 *	ns	-0.047 *
Uniformity CV%	ns	ns	+0.010 **
Breaking Strength	ns	+0.299 *	ns
Elongation Percent	+0.0036 ****	+0.011 ****	+0.002 *
Breaking Tenacity	ns	+0.123 *	ns

ns = p > 0.1; *, **, ***, **** indicate p < 0.1, 0.05, 0.01, and 0.001 respectively.

Table 16. Relationships between blue-dyed fiber color components and heat-unit [DD16 accumulations at 50 and 100 days after planting [DAP] and at harvest. [1991 and 1992 data pooled for four genotypes, DPL20, DPL50, DPL90, and DPL5690.]

Color Component	Slopes of DD16 versus Yarn Property Regressions and Regression s Equation Significance		
	0 to 50 DAP	50 to 100 DAP	At Harvest > 150 DAP
+L [Lightness Color Component]			
+L, smooth	+0.0011 ***	+0.0043 **	ns
+L, looped	+0.0012 ***	+0.0039 ***	ns
-a [Greenness Color Component]			
-a, smooth	ns	ns	+0.0004 ***
-a, looped	+0.0002 **	ns	+0.0007 ****
-b [Blueness Color Component]			
-b, smooth	-0.0009 ****	-0.0032 ***	-0.0006 *
-b, looped	-0.0011 ****	-0.0032 ****	-0.0012 ****

ns = p > 0.1; *, **, ***, **** indicate p < 0.1, 0.05, 0.01, and 0.001 respectively.